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Design of a temperature profiling system for use in thermal processing of food products

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Design of a temperature profiling system for use in thermal processing of food products

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1. Introduction.

In the last decades, people have become more dependent on ready to eat (RTE) products that are cooked in processing establishments, not by the direct consumer. These RTE meat and poultry products were defined by the United States Department of Agriculture – Food Safety and Inspection Service as “products that have been processed so that they may be safely consumed without further preparation by the consumers; i.e., without cooking or application of some other lethality treatment to destroy pathogens” (USDA-FSIS, 2001).

The market for RTE meat and poultry products is rapidly increasing. Consequently, it becomes more and more important to ensure the food safety of these thermally processed retail products. Recent recalls on these RTE products, and foodborne related illnesses have led to serious concerns over the safety of these products (CDC 2000; FSIS-USDA 2004). Therfore, the primary concern of food manufacturers today has become the production of safe food, free of foodborne pathogens.

Fortunately, thermal processing is an effective means of eliminating food borne pathogens from meat and poultry products (Murphy et al., 2002). Thermal destruction of pathogens is a time-temperature dependent process. The time-temperature relationship of thermal inactivation of pathogens known as lethality is expressed in terms of D- and z-values. The D-value is defined by the time required to cause 90% of reduction of the microbial population at a specific temperature. The z-value is the temperature difference required for the thermal inactivation curve to cause one logarithmic reduction (Murphy et al., 2004). From a known z-value, process lethality (L) can be calculated as:

$$L = \int_0^t 10^{\left[\frac{T(t)-T(ref)}{z}\right]} dt$$

where T(t) is the product temperature at time t, and T(ref) is a reference temperature. The z-value should be known in order to calculate the process lethality during cooking, and it is calculated from known D-values at different temperatures (Doyle and Mazzotta, 2000).

The USDA-FSIS (1999) recently made final pathogen reduction performance standards applicable to the production of certain meat and poultry products. The performance standards establish a requisite reduction of *Salmonella* (lethality) in certain ready-to-eat products and limit the growth of spore forming bacteria of concern (stabilization) in certain ready-to-eat and partially-cooked products. To achieve the lethality performance standard, food processing establishments are required to achieve a 7-log10 reduction in *Salmonella* in ready-to-eat poultry and a 6.5-log10 reduction in *Salmonella* in ready to- eat beef products (Murphy et al., 2002).

To help food processors meet this regulation, USDA-FSIS issued a guideline that cooked poultry products should reach an internal temperature of at least 165°F before being removed from the cooking medium (USDA-FSIS, 2006). However, production volumes typically exceed 100 pounds per minute, so when products are in a small size, less than 1% of the product items are actually being inspected.

To calculate the process lethality it is necessary to know the change in the internal temperature of the product throughout the entire cooking process. To achieve this, food processors need to have a device that can record temperature measurements and withstand the harsh conditions in the oven during the whole cooking process. However, current industrial practice is to sample a small fraction of cooked meat and poultry temperatures by inserting a food thermometer into the meat immediately after cooking (Richardson, 2004).

The purpose of this study was to develop a thermal inspection system on a full scale meat and poultry product line. The system must withstand the production and sanitation environments and adapt to the many different products and conditions present on a common product line. By using this device, food processors will be able to measure the internal temperature of the product during its entire cooking process. This will provide certainty to food processors if the product reached the required internal temperature by USDA standards as well as proof of their processes.

2. Objectives & Constraints.

The design should comply with the following characteristics:

- The device is to be a data-logging system designed to transit through industrial ovens, along with the product being processed.
- The data logger should be protected from the extreme temperatures of the process.
- It should be appropriate for climate and working conditions
- It should be simple to manufacture and repair.
- Its handling should be safe for the operator.
- Its dimensions should be in accordance with the 3.75 in. maximum height of entrance and exit of the Stein oven at the pilot plant in the University of Arkansas.

The following constraints must be met by the design:

- The internal temperature of the device should range between -25°C and 80°C to keep safe the circuit connections.
- The smaller the size of the data logger the better.
- The data logger battery life should last a minimum of 6 months.
- The data logger memory capacity should be big enough to record 8 hours of processing.
- The data logger should have a USB connection so data can be easily transferred into a computer.

Once a working prototype of the device is built, testing on reading the internal temperature of meat product should be performed as well as testing for providing proof of bacteria destruction on meat or poultry products through thermal processing.

3. Potential Solutions.

Of the many transducers available for temperature-measurement applications, thermocouples are among the most common. They are cost effective, have standard connectors, and can measure a much wider range of temperatures than other sensors like resistance temperature devices (RTDs), thermistors, and temperature-sensing integrated circuits (ICs) (Carstens, 1993).

Thermocouples are constructed with two wires made from different metals. When these two metals are joined (i.e., welded or soldered) to form two junctions, the voltage generated by the loop is a function of the temperature difference between the two junctions (hot and cold junctions). Knowing both the temperature of the cold junction and the temperature of the hot junction relative to the cold-junction temperature, the actual hot-junction temperature can be determined. To facilitate this, a cold junction compensation device can be used (Carstens, 1993).

Analog Devices Inc. (www.analog.com) offers the AD595 amplifier and thermocouple cold junction compensator on a monolithic chip. It is intended for use with a Type K thermocouple, which consists of the alloys chromel and alumel. The AD595 chip is capable of creating an output voltage that is linearly related to the temperature of the thermocouple junction. For even greater convenience, the output voltage is by default set to 10 mV/^{o}C. Thus, voltage readings can be converted to temperature (°C) by multiplying the value times 100.

3.1 Storage and data acquisition: Lascar electronics (www. lascarelectronics.com) offers a data logging system known as EL-USB3 (see figure 1) and it measures and stores up to 32,510 voltage readings and can transfer the stored data by plugging the module straight into a PC's USB port. The data logger comes with the EasyLog USB software application, which facilitates the transfer of the data from the logger into the computer. Once the data is transferred from the data logger, the software allows the user to transfer the data to different software applications.

Figure 1: EL-USB3 Data logger (lascarelectronics.com)

Table 1: Manufacturer' specifications of EL-USB3 data logger (Lascarelectronics.com)

Specifications	Minimum	Typ.	Maximum	Unit
Internal Resolution	-	50	-	mV d.c.
Accuracy	-	±1	-	%
Logging Rate	Every 1 second	-	Every 12 hours	-
Operating Temperature	-25(13)	-	+80(176)	°C(°F)

3.2 Housing: The housing of the device must protect the data logger, the AD595 chip and the circuit components when subjected to thermal processing. Therefore, the housing of the circuit should be able to withstand the harshest industrial cooking environments and therefore have high heat resistance. It should also provide sufficient space for the wiring, and be in accordance with the established dimensions for the device. For food applications, housings are often made of stainless steel; however, housings made of ceramic represent an advantage since they are very good heat insulators. For this reason, the housing of the device is to be made out of ceramic with the restriction that the container should not exceed 3.75 in. of height.

3.3 Insulation: The main issue is to maintain the components of the device at a temperature below 80ºC (maximum operating temperature for the data-logger) and ensure a safe range of temperature while the oven is operating at 400°F(204.4ºC) over twelve minutes cooking time (approximated cooking time for a sample of poultry meat).

- ✓ **Mineral fibers (insulation blankets):** They offer the following advantages: high resistance to fire, high resistance to microbiological attack, good resistance to most chemicals, and high heat resistance (Carstens, 1993).

  Unifrax Corporation (www.unifrax.com) offers an excellent insulation blanket known as FyreWrap®. It is a lightweight and a high-temperature resistance insulation blanket, designed to provide single layer enclosure for combustible items located within fire-rated return air plenums. Thus, it can stand temperatures up to 1000°C (1832°F) and it has low thermal conductivity (0.018 $W\,m^{-1}\,°C^{-1}$) in comparison to common insulation blanket like fiberglass (0.04 $W\,m^{-1}\,°C^{-1}$).The core material of this insulation blanket is known as Insulfrax ®, which is a combination of calcia, magnesia, and silica.

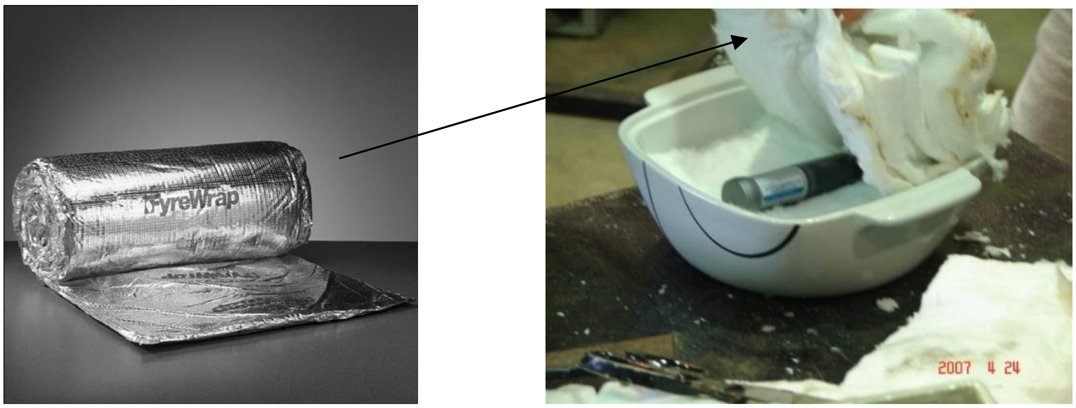

Figure 2: Insulation Blanket roll (left) and preliminary design with ceramic housing and insulation blanket (right)

Selection of insulation materials should be based on initial cost, effectiveness, durability, and the adaptation of its form/shape. Materials should have a low thermal conductivity to reduce the total coefficient of heat transmission (Carstens, 1993). Also, materials need to be rated as non-flammable and specially non- toxic, since the device is to be exposed to food products. FyreWrap® insulation blanket was chosen to prevent excessive increases in the internal temperature of the device (See Figure 2). Two other techniques were studied for protecting the device from excessive temperatures. First, the ceramic enclosure and the components inside were cooled in a refrigerator before being tested in the oven. When it was found that this pre-cooling was not adequate to prevent excessive temperatures in the enclosure during the tests, modifications were made so that a small quantity of dry ice could be placed within the enclosure to assure a safe operating temperature for the circuit components (<80°C).

4. Preliminary Design

4.1 Circuit blueprint

The circuit contains a thermocouple (type K), an AD595 chip, a 9-volt battery, and the EL-USB3 for data acquisition. Figure 3 shows the diagram and the picture of the circuit set up. Notice that pins 1, 4, 7, and 13 were grounded to the negative end of the 9-volt battery. The positive pole of the 9-v source was connected to pin 11, and the thermocouple was connected to pins 1 and 14. Pins 8 and 9 were directly connected to the positive input of the data logger. The negative input of the data logger was connected to the negative pole of the battery as seen in Figure 3 (top). All of the circuitry shown inside the rectangle that represents the chip is internal to the chip.

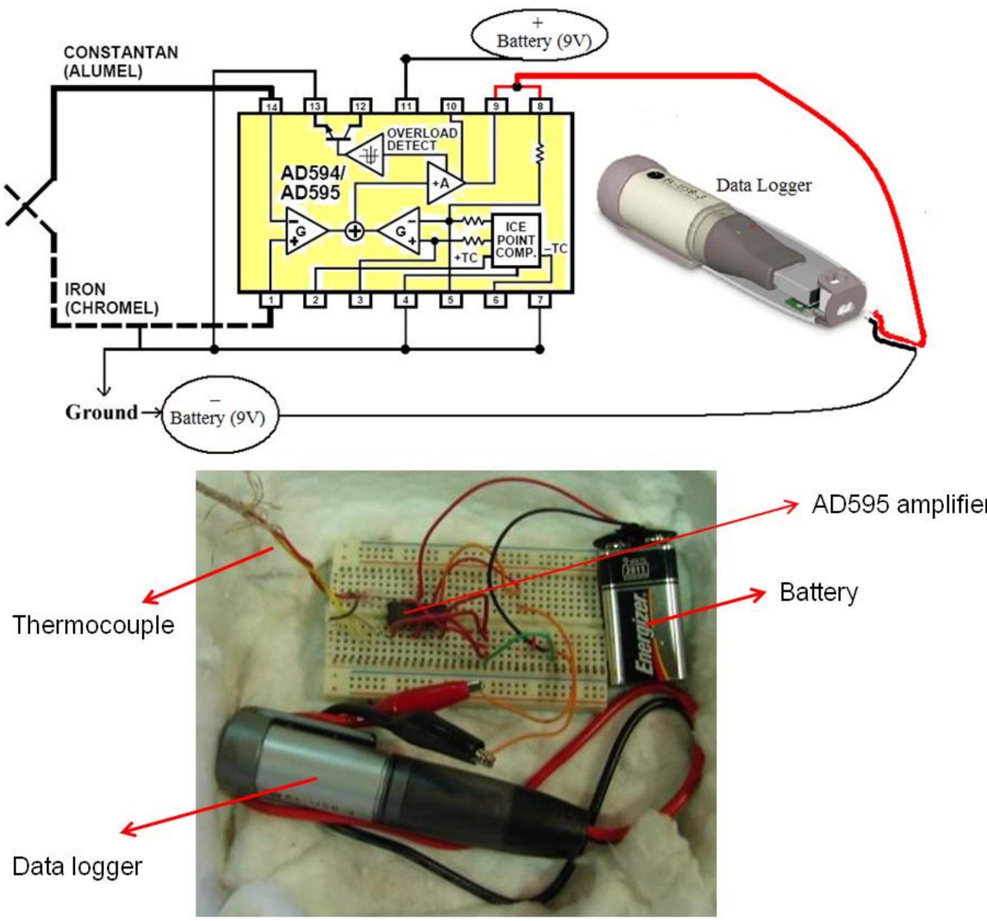

Figure 3: Sketch (top) and picture (bottom) of circuit blueprint

4.2 Further details of preliminary design: The housing for the device was chosen to be a ceramic container (baking dish) of 3.5 in. of height, 8 in. wide and 8 in. long. The insulation chosen consisted of FyreWrap® insulation blankets, which covered the circuit components. See Figure 4 for illustration of preliminary design.

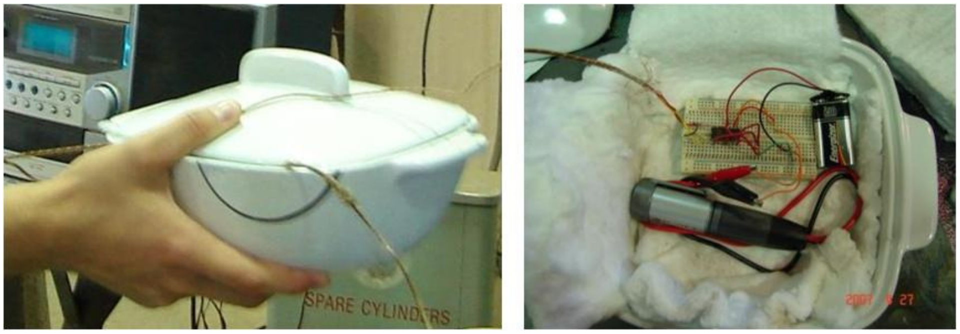

Figure 4: Preliminary design.

The device was designed to transit through the oven, along with the product being cooked. The goal was to avoid damaging the data-logger, which was the limiting component, by preventing excessive high temperatures for at least 15 minutes. Therefore, the aim was to keep the data-logger and the circuit components at or below their safe operating temperature (80°C).

To test the insulation, the ceramic container with some of the FyreWrap® was placed in a conventional oven.   A thermocouple was placed inside the insulation in the container so that temperature within the insulation could be monitored for a period of 10 minutes. The thermocouple was connected to a digital voltmeter through an AD595 chip (See Figure 5). The internal temperature after 7 minutes remained at 65°C under an oven temperature of 200°C. Although the temperature did not reach the maximum allowed (80°C), it was felt that improvement on the insulation was needed to assure a safe operating temperature for the circuit components when placed into the Stein oven, where higher heat transfer rates were expected.

Device ready to go into the oven | Testing station | Circuit set up to monitor temperature changes inside the device while in the oven

Figure 5: Testing Insulation for Preliminary prototype.

5. Final Prototype.

The device is a data logging system designed to transit through a pilot-plant oven, along with a product being thermally processed. A thermocouple connected to the data logger can then be placed into the core of the product to be processed such that the user can obtain temperature information for every moment of the cooking process. The temperature history recorded in the data logger can then be downloaded and viewed with Windows software.

Insulation is an important part of the system, since it provides protection for the electronics from the high temperatures used in food industry processing. The data logger itself is protected from the extreme temperatures of the process by a secondary insulated ceramic container which encloses the circuit components as well. This container has dimensions of 2 in. height, 4 in. long and 4 in. wide. It also contains FyreWrap® layers covering the circuit components and the data logger. This ceramic container was placed inside of the housing of the device (a ceramic baking dish).

The housing of the final prototype was changed to a container of dimensions 3.25 in. of height, 8 in. width and 8 in. long. The container was modified from its initial design due to the fact that the original container did not comply with the size constraints of the project. In addition, layers of FyreWrap® were placed between the circuit's container and the housing of the device so that heat transfer to the circuit components could be minimized.

Small pieces of dry ice were placed on top of the FyreWrap® insulation cloth in order to keep cool the interior of the device for a longer period of time. Dry ice was used because of its low temperature and direct sublimation to gas, which makes it a very effective coolant. It is a good alternative since it does not cause damage to the circuits while being under high temperatures.

Finally, to minimize heat coming into the device, the lid of the container was sealed with aluminum foil tape, an excellent vapor sealant that can withstand up to 500°F (Carstens, 1993). Figure 6 shows the inside of the device, as well as the prototype ready to go into the oven along with the product. Notice in Figure 6 (middle) that dry ice was placed on top of a silicone sheet. This silicone sheet prevents dry ice from getting into the circuits components as well as adding extra insulation to the circuit.

Figure 6: Final Prototype

5.1 Cost Analysis.

The following table gives the costs of manufacturing one device with the description of the final prototype.

Table 2: Cost analysis of the final prototype.

Item	Location	quantity	Cost
Larscar EL-USB 3	Lascarelectronics.com	1	$72.00
AD595 chip	Analog.com (14 pins @ $13.76)	1	$1.00
Circuit's container (ceramic)	Wal-Mart stores	1	$2.95
Housing (ceramic baking dish stoneware)	Kohl's	1	$20.00
Dry ice	Wal-Mart stores	1 lb	$10.00
FyreWrap®	Insufrax.com	1 ft.	$6.31
Silicone baking sheet	Wal-Mart stores	1	$7.50
Aluminum foil tape	Lowes stores	1	$11.50
		Total =	**$129.26**

6. Testing

6.1 Prototype testing

The device presented in this paper is a data logging system designed to transit through an industrial oven, along with the product being thermally processed. The main goal of the design process was to keep the internal temperature of the device cool enough that the circuit components as well as the data logger are safe to operate for over 15 minutes under direct steam and air impingement at a temperature of 400°F (204.4ºC).

To test the internal temperature of the device a thermocouple was initially inserted instead of the circuit components. The pilot-scale air/steam impingement Stein oven (model 106) of the poultry science department of the University of Arkansas was used for testing the device. The device was placed on the conveyer belt of the oven and remained at 400°F for 15 min. The thermocouple was connected to the IDL-800 digital voltmeter through an AD595 chip to monitor the changes in temperature during the 15 minutes process. After the first 7 minutes the internal temperature of the device remained between 20°C and 28°C (see Figure 7). This procedure was repeated 5 times giving the same temperature range for the internal temperature of the device. Also, the amount of dry ice included in the device was kept to $7_{1/4}$ oz to get similar temperatures ranges for each trial.

Figure 7: Initial testing. Stein oven at the pilot plant (left) and testing set up (right)

After testing the insulation, the data logging system was placed into the device. However, the thermocouple length was shortened so that it could read the temperature of the surroundings of the circuit components and the data logger. Then, the device was sealed with the aluminum foil tape and placed on the conveyer belt of the oven and remained under steam/air impingement at 400°F for 13 minutes. The following graph shows the data saved on the data logger for this test.

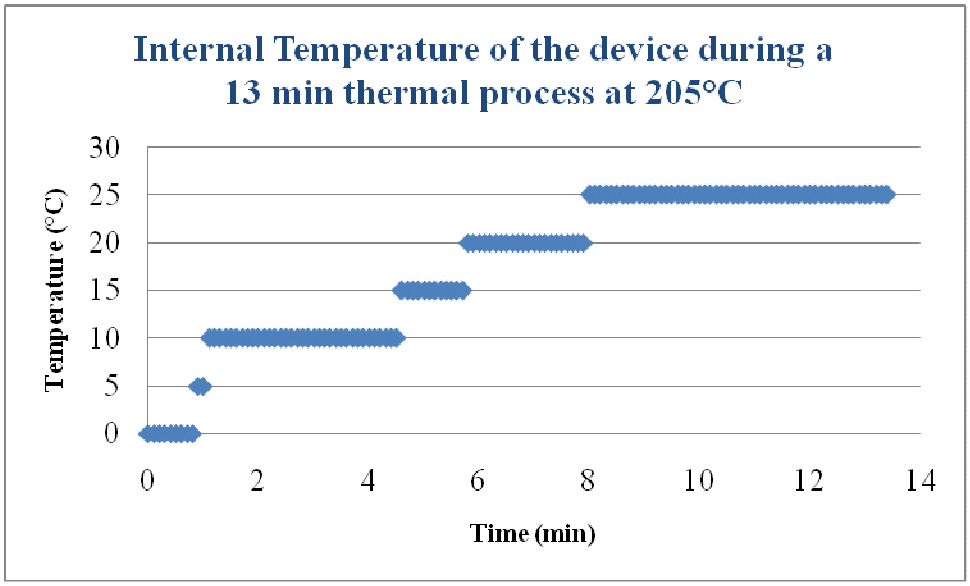

Figure 8: Internal temperature of the device being tested under 205C in the Stein oven for over 13 minutes

This test procedure was performed 4 times (2 of these 4 tests were done for 15 minutes) so that we could be sure that the internal temperature will remain at the same temperature range of 20-28°C. Notice in figure 8 that temperature reading at time zero is 0°C (due to the dry ice). This is still a safe operating temperature since the operating temperature range for the data logger and circuit components was specified to be from -25°C to +80°C. The results shown in figure 8 were very similar to the other trial runs, where it was observed that after 8 minutes of testing, the temperature remained at 25-26°C. Consequently, it was proven that the device is able to withstand the production and sanitation environments present in industrial thermal processing of food products.

6.2 Bacteria testing.

Thermal Processing is a primary means of eliminating pathogens from meat products and therefore serves to protect against foodborne disease. Ready to eat meat and poultry products can be consumed without further cooking. Therefore, the presence of pathogens in these products could present a food safety threat. Since 2002, hundreds of recalls have resulted in the loss of millions of pounds of meat and poultry products as well as millions of dollars due to the concern of possible contamination with foodborne pathogens (FSIS-USDA 2004). Among these pathogens is *Listeria monocytogenes.*

L. monocytogenes, a gram-positive, non-spore forming, facultative, rod-shaped bacterium, causes listerosis in young, old, pregnant and immunocompromised people with symptoms that could lead to death (Bean and Griffin, 1990). The thermotolerance of *L. monocytogenes* is estimated to be one of the highest among nonsporeformers (D'Sa et al., 2000).

In an effort to eliminate foodborne illness, the USDA has implemented a performance standard that requires a reduction in the population of foodborne pathogens in certain fully cooked and partially cooked poultry products equivalent to treating the product for a period of time equal to 7xD, where D is the decimal reduction time. The performance standard requires that the processor provide the supporting information for the hazard analysis and decision-making documents associated with the development of Hazard Analysis Critical Control Point (HACCP) plans, critical limits, selection and frequency of monitoring, and verification procedures. The performance standards aim at ensuring product safety and also giving establishments the flexibility to adopt science-based processing procedures and controls (USDA-FSIS, 1999).

The objective of this study was to monitor the internal temperature of chicken breasts contaminated with *Listeria* during air/steam impingement cooking as well as to determine the level of pathogen destruction in the final product.

6.2-1 Material & Methods:

Although it would be advantageous to evaluate *L. monocytogenes*, it is generally undesirable to risk working with this pathogen in a food-processing facility. Often, biological indicators are used in challenge studies, because they are nonpathogenic and typically more heat-resistant than pathogens, thus providing resistance information with a margin of safety (Fairchild and Foegeding, 1993). Therefore, *L. innocua* strain, a thermal resistance indicator for *L. monocytogenes,* was used in this study.

6.2-2 Bacterial inoculation and product preparation:

Raw chicken breasts were obtained from a local grocery store and divided into three different pieces of approximately 3oz of weight each. Each of the three chicken breasts were initially inoculated with 0.3 mL of 10^9 cfu/mL of *L. innocua*; a non-pathogenic Listeria strain.

A pilot-scale air/steam impingement oven was used in this study to cook the chicken breast. The oven air temperature was 204.4°C with an air circulation of 13 m^3/min and moisture content of 60% (vol/vol) in the oven air.

Each chicken piece was placed on the conveyor belt. During cooking, a thermocouple probe (type K) was placed at the center of each piece. The temperature was monitored every 10 seconds by using the prototype. Each sample was then cooked until its core temperature reached 165 °F (12 minutes approximately cooking time per piece). After cooking, the chicken breasts were cooled at ambient temperature (25°C).

6.2-3 Bacterial enumeration:

After each chicken breast was cooked, it was placed in a sterile bag and 0.9 mL of phosphate buffer saline solution (pH 7.0) was then added to each bag. Chicken breast pieces were labeled as sample A, B, and C, respectively. Each sample was rubbed with the solution for two minutes, to ensure that the buffer solution and chicken juices were evenly distributed. Next, serial dilution techniques were used to inoculate Petri dishes with varying dilutions of liquid extracted from each chicken bag. The petri dishes used contained MOX (modified oxford medium) which is selective for *Listeria innocua*. For each sample, three Petri plates at 10^{-1} dilution and two Petri plates of 10^{-2}, 10^{-3}, and 10^{-4} dilution were incubated for 48 hours at a temperature of 37 °C. In addition to the Petri plates, a sheet of Petri film was inoculated per each sample at a dilution of 10^{-2} and incubated for 48 hours at 37 degrees °C.

7. Results & Discussion.

The MOX plates were observed for signs of contamination. After 48 hours of incubation it was observed that there were no signs of *Listeria* growth, even at the -1 dilution. This was true for all three chicken breasts samples. In addition, the data acquired from the data-logger provided the internal temperature of the chicken samples during the entire cooking process. Notice in figure 10 that after 12.4 minutes of cooking, the internal temperature at the core of the chicken sample reached 74°C(165.2°F), which satisfy the USDA guideline of at least 165°F internal temperature for poultry products (USDA-FSIS, 2006).

Figure 10 shows that there is a peak in the curve before the end point where the product is out of the oven. At this peak, the acquired data shows that after 10.2 minutes of cooking time, the internal temperature at the core reached 80°C (176°F). Without using the device presented in this work, it could not have been possible to measure the internal temperature of the chicken breast sample.

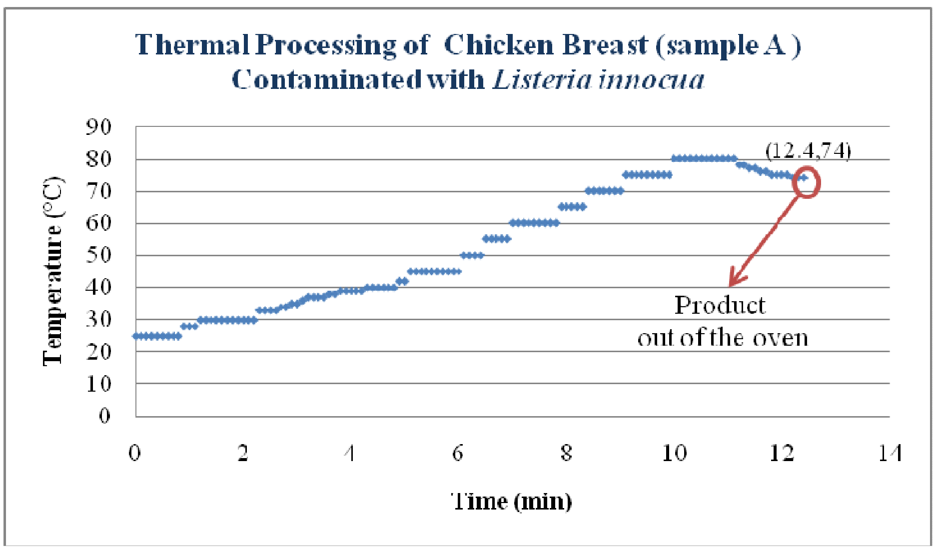

Figure 9: Thermal processing of contaminated chicken breast (sample A)

It is important to mention that it took the product 23 seconds to reach the point where it received the steam for cooking, and it took the same amount of time for the product to reach the point where food processor will insert the probe to measure the internal temperature of the cooked product. Therefore, the temperature values measured by the food processor would be lower than the actual temperature of the product at the point of removal from its cooking medium.

Figure 10 shows how the internal temperature at the core of food products is currently measured during thermal process. This is done once the product is out of the oven where the technician inserts a probe into the core of the product making sure the temperature reads at least 73.5°C (165°F).

Figure 9: Cooked product being measured as soon as it has left the oven.

The temperature measurements done by the technician were compared with the data saved by the data logger of the device. Notice in Table 3 that the divergence in values is due to the difference in sensitivity of the device and the one used by the technician. However, these results proved that the device was capable of record accurate readings for the entire thermal process of the chicken breast samples.

Table 3: Comparison of temperature measurements of the chicken breast samples taken at the end of their cooking process.

Sample	Technician (temperature, °C)	Device (temperature, °C)
A	73.8	74
B	75.5	76
C	74.6	75

8. Conclusions.

The device presented in this paper offers a reliable method of measuring the true product temperature during its entire thermal processing. It also allows users to utilize the acquired information into process optimization. Testing of the prototype showed that the device is able to withstand harsh environment conditions and that it is able to provide accurate data of the cooking process. It represents a great advantage for food industries since it is a simple way of providing full process validation documentation to satisfy government requirements and customer necessities for safer food products.

Current performance standards require processors to validate the efficiency of their thermal processes to reduce microbial contamination. This device not only provides the entire temperature profile of the cooking process, but also provides the information needed for determining process lethality. The USDA-FSIS issued guidelines to the fact that cooked poultry products should reach an internal temperature of at least 165°F before being removed from the cooking medium (USDA-FSIS, 2006). Currently this is achieved by inserting a probe at the core of the product when it is out of the oven. However, it takes few seconds for the product to leave the oven where it loses heat. By using the developed device, food processors would be able to obtain real measurements for their processes and provide proof that the core temperature of the product has reached the USDA-FSIS guidelines before it cools. Other advantages of using the proposed device include the ability to identify problems in the process before affecting the quality of the product, increase productivity, minimize fuel consumption, and control product quality.

8.1 Some suggestions for further work.

- Test the device at temperatures above 400°F and for periods longer than 15 minutes to determine maximum operating points of the device.
- Find an alternative for the dry ice. Dry ice requires special handling that may cause some delay on industrial processing.
- Include other applications on the device like being able to measure product’s water content, or monitor different products at the same time.

9. Acknowledgments.

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